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A flexible portable proton exchange membrane fuel cell

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HIGHLIGHTS

► A flexible portable proton exchange membrane fuel cell (PEMFC) has been developed.
► Its non-directional flexibility is acquired with carbon fibre current collectors.
► It performs well when bent to curvatures with various radii in any directions.
► Current collector is composed of several metal wire embedded carbon fibre bunches.
► Flexible carbon fibre has low contact resistance under very low compression force.

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ABSTRACT

A flexible portable proton exchange membrane fuel cell (PEMFC) is developed with non-directional flexibility acquired through new carbon-fibre-made current collectors and a new cell structure. The performance of a pilot cell suffers no significant loss when bent to curvatures with various radii in multiple directions. It also compares well with a nonflexible cylindrical portable PEMFC composed of similar components.

The new cell is made with a single cup-like flexible main body with the membrane glued to the inside rim. The current collector is composed of several bunches of carbon fibre, each with metal wires embedded in them. The soft and flexible fibres not only allow for close and evenly-distributed contact with the bent electrode, but also change the character of the contact so that a large compressional force is no longer required to acquire low contact resistance which is, above all, the key to the success of this flexible cell design. The metal wire provides the needed flexibility to cover large curved electrode areas. A wire spring is used to pressure the collector against the electrode while the main body bends.

1. Introduction

Progress in the development of hydrogen storage, such as metal hydride and chemical generation [1–4], has promoted the commercialization of portable PEMFCs [5]. A portable PEMFC should be able to run anywhere anytime like a conventional battery. The best way for an air breathing fuel cell to breathe would be to attach it to the surface of a bag, backpack or belt, which requires the cell to be light, flexible and resilient.

To date, most researches have concentrated on issues related to cell size and weight. Many portable PEMFCs have been developed with output power ranges from a few milliwatts to several watts [6–9], and constructing a flexible portable PEMFC seems feasible because the cell's key component, i.e., the membrane electrode assembly (MEA), is flexible. Other components such as the current collector and the fuel compartment, either as standalone devices or combined into a single body, (i.e., a bipolar plate) can all be made with flexible materials. Kim et al. [10] used a thin flexible printed circuit board as a current collector to reduce the volume of an air-breathing monopolar stack, but the resulting planar stack was not flexible. Zhang and Hsing [11] used flexible graphite material to produce an anode structure to serve a dual role as a liquid diffusion layer and flow field plate but, again, the resulting cell is not flexible. Ito et al. [12] developed a micro direct methanol fuel cell (DMFC). Ten such devices, each with a diameter of 0.5 mm, were fabricated in two rows on a polymeric flexible substrate, using thin Au film as the current collector. The authors claimed that the maximum output power drops only 20% as the cell bends, but difficulties arising from bending are not fully disclosed in this design because the electrode area of an individual cell is only 0.2 mm^2 and the electrode only accounts for less than 0.35% of the total area of the substrate (2 of 600 mm^2).

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In conventional designs, force is used as the primary means to reduce the contact resistance between connected elements. This is effective for flat and relatively hard contact surfaces. The larger the force is, the smaller the resistance will be. It is essentially reshaping the contour of the contacting surfaces to create more contact points in a broader area. Heavy and bulky components must be used to exert this large force and, subsequently, all other components have to be thicker or stronger to withstand the pressure, even to the extent of sacrificing performance and, eventually, cell flexibility.

Thus making a portable fuel cell light and flexible requires the development of new flexible components. More importantly, the cell structure and the character of the contacts between components inside the cell must be changed so that a large compressional force and rigid fastening devices are no longer required to reduce the contact resistance.

2. Experimental

This flexible cell is designed so that everything bends with the originally flexible MEA, thus requiring that all other components must also be flexible. In addition, the current collector must fit the curved electrode surface. Finally, and most importantly, the design must avoid using a large compressional force to acquire a low contact resistance. The new design differs from the conventional one as follows.

2.1. Current collector

The current collector is the most important component in this new flexible cell because existing designs mandate the current rigid structure in conventional cells. Conventional current collectors usually have a flat and relatively hard surface that relies on a large compressional force to reduce the contact resistance. Therefore, the new current collector must avoid having that kind of contact.

The current collector is made of carbon fibre because of its flexibility and chemical stability. Stacking millions of fibres in parallel compensates for the relatively high electrical resistance of any individual fibre. The diameter of the individual carbon fibres is about 6 μm, and there are more than 2 million fibres per square centimetre so that the electrical resistance of the fibre itself may be disregarded. At one end, the soft and flexible carbon fibre touches the electrode to transmit electrons. The other end is tightly glued to a conducting metal wire to minimize the total electrical resistance. However, binding with epoxy will rigidify the collector so it is further divided into a few lumps connected with the metal wires as illustrated in Fig. 1. The flexibility of the collector comes from the wire between the fibre lumps and the soft fibre itself. The major advantages of this design are as follows:

2.1.1. The carbon fibre current collector has low contact resistance

According to Holm [13], contact resistance is mainly the constriction resistance, thus the evenness of the distribution of the contact spots has a greater effect on the resistance value than their number.

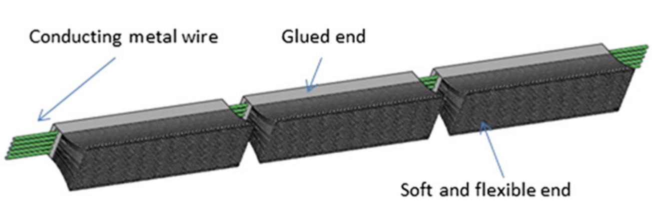

Fig. 1. Flexible current collector made of carbon fibre and embedded metal wires.

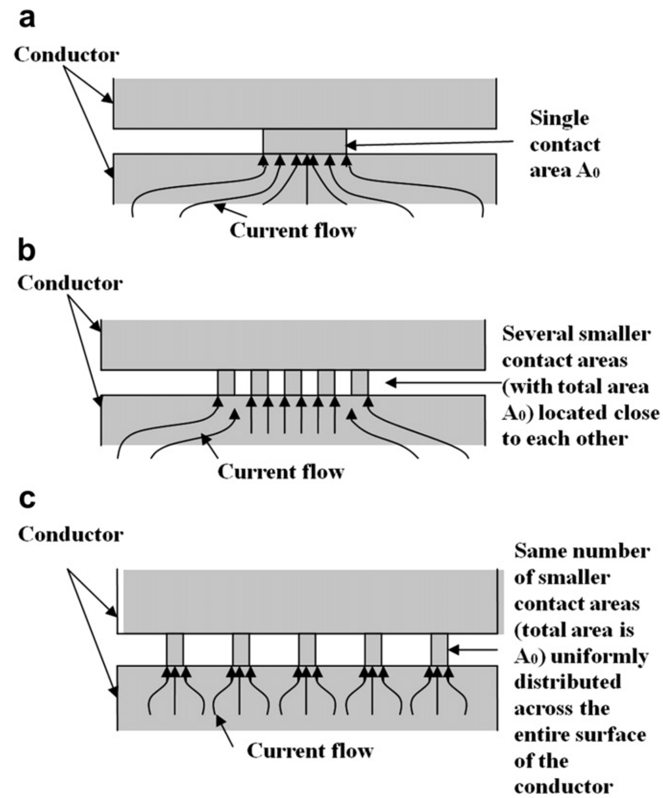

Fig. 2. Constriction (contact) resistances of three different contact point situations. Constriction resistance comparison: (a) > (b) > (c).

Holm examined the constriction (contact) resistance under various contact conditions, and demonstrated the impact on constriction resistance of disuniting a contact area into several equally sized spots and increasing the distance between them. If a single contact area is divided into n uniformly distributed smaller circular contact areas of radius a, and the distance between the centres of two neighbouring contact areas is $2l$, then the contact resistance decreases as la^{-1} increases. In other words, keeping the total area of contact constant, the larger the number of contact spots, the smaller the contact resistance. Furthermore, keeping the

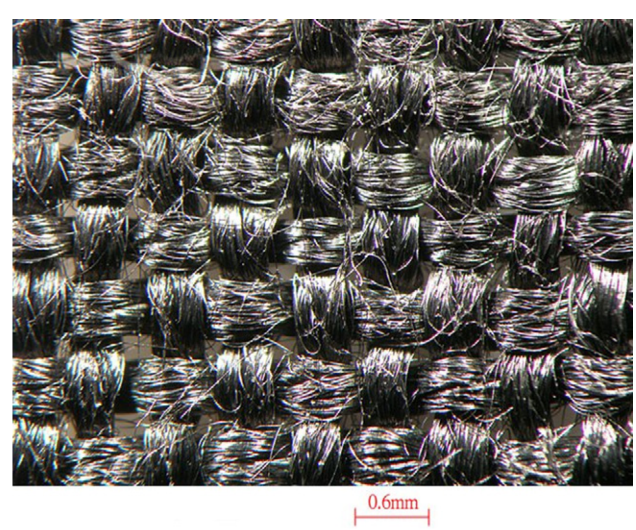

Fig. 3. A microscopic picture of the carbon cloth from E-Tek Co.

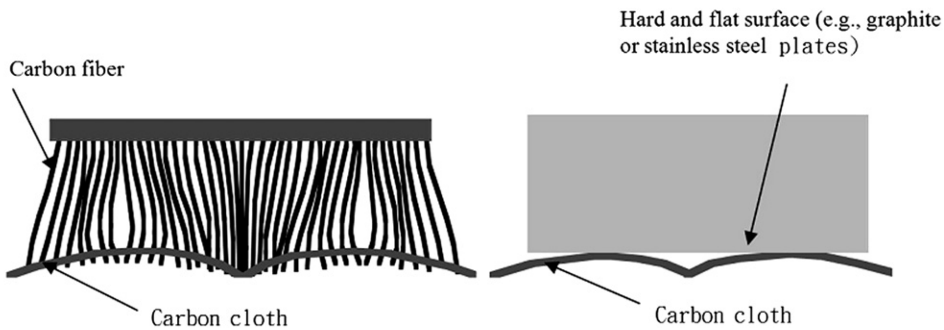

Fig. 4. Characteristics of the contacts between the carbon cloth and carbon fibre bunch vs. between carbon cloth and materials with hard and flat surfaces (e.g., graphite or stainless steel plates).

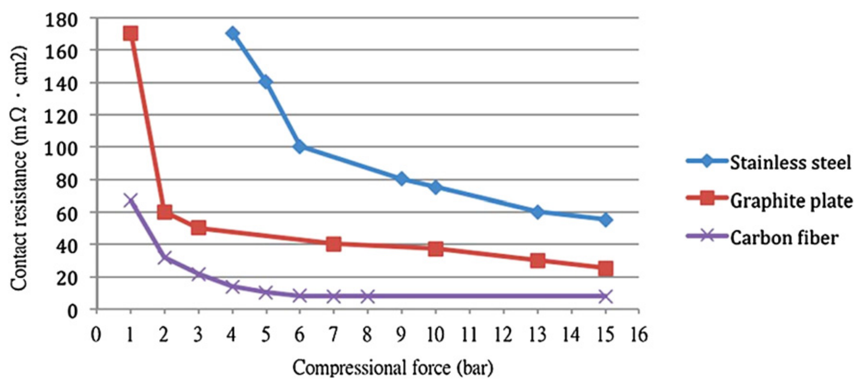

Fig. 5. Contact resistances between carbon cloth and different materials at various compressional loadings.

total area of contact and the number of contact spots constant, the contact resistance decreases as the degree of scattering of the contact spots increases, as illustrated in Fig. 2.

Fig. 3 presents a microscopic picture of a carbon cloth from E-Tek, clearly showing that not every point on the surface of the cloth can make direct contact with the hard and flat target surface (e.g., a graphite or stainless steel plate) unless a very large force is applied to essentially even the convex and concave portions. However, each loose and flexible carbon fibre in the new design can touch the cloth directly. Fig. 4 shows that the contact spots associated with the graphite plate are mainly gathered around the convexities on the surface of the carbon cloth, whereas those associated with the carbon fibre bunch are more uniformly distributed over the entire surface. As shown in Fig. 5, the experimental results indicate that the carbon fibre has the lowest contact resistance.

2.1.2. The carbon fibre current collector doesn't require a high compressional force

In the proposed carbon collector, the tips of the soft and flexible carbon fibres adapt to the contact surface and, once the contacts are made, a larger compressional force will not significantly change the number or the distribution of contact points to reduce contact resistance. As shown in Fig. 5, the contact resistance of carbon fibre drops quickly and remains almost unchanged after compressional loading of 5 bars whereas the resistance of the graphite plate will continuously decrease as the applied force increases.

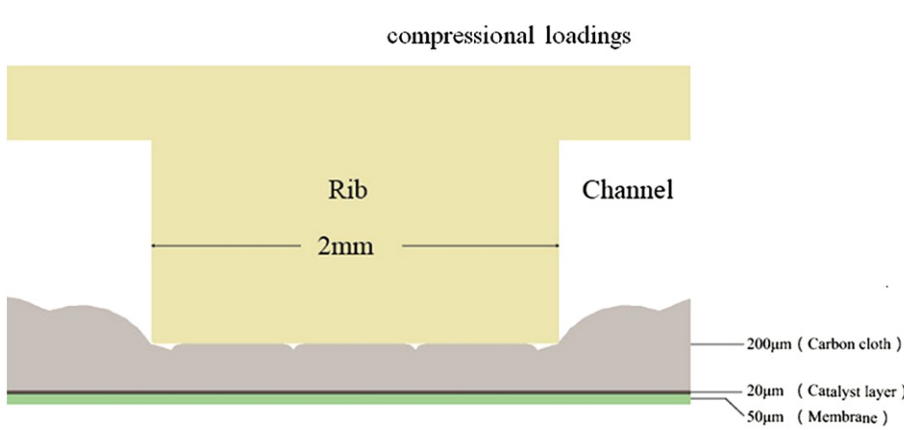

Fig. 6. Exact scale of the components inside a cell.

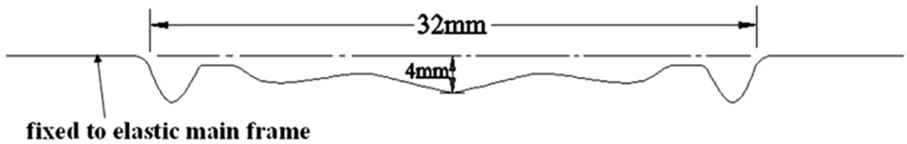

Fig. 7. Spring retainer for the carbon fibre current collector.

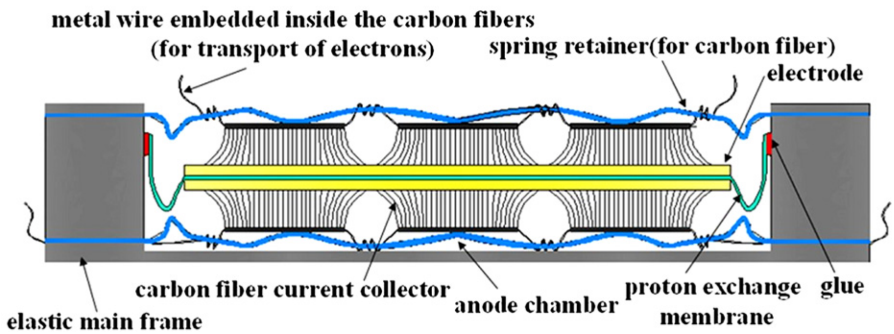

Fig. 8. Structure of the new flexible cell design.

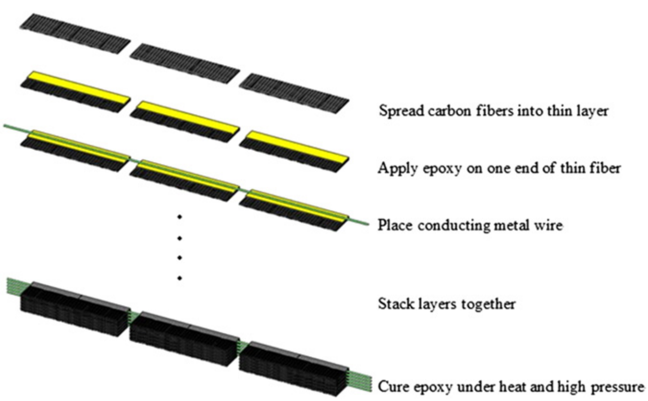

Fig. 9. Fabrication processes of the lumped carbon fibre current collector.

This is the most important characteristic associated with the carbon fibre current collector because it eliminates the need for a large force and the rigid components needed to apply it, thus "loosening" the cell design.

2.1.3. The carbon fibre current collector does not hamper the diffusion of GDL

Fig. 6 is drawn to scale to show the relative sizes of the cell's components. It is clear that the best and shortest path to supply fuel to every catalyst particle would be the one directly below the channel. For those catalysts directly under the rib of the flow field plate, fuel supply depends on the diffusion capability of the gas diffusion layer (GDL) itself as well as the gaps between the bipolar plate and the GDL. However, applying a large compressional force narrows all the passageways, thus limiting fuel transport and affecting performance as current load increases. The carbon fibre current collector, however, does not deform the GDL and fuel diffusion thus remains almost constant for catalysts under the rib

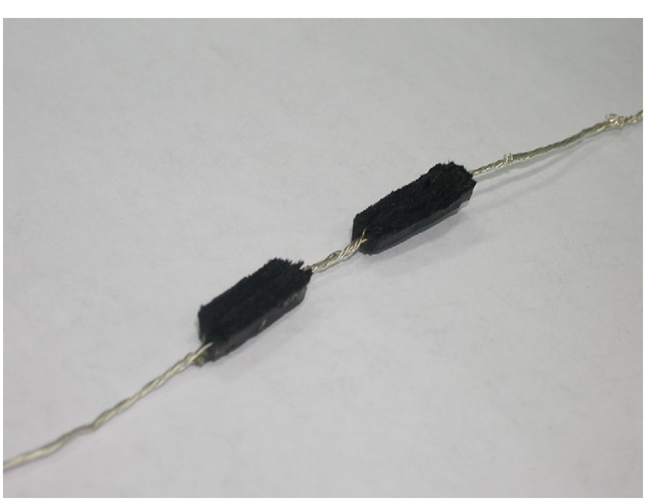

Fig. 10. Current collector composed of two carbon fibre lumps.

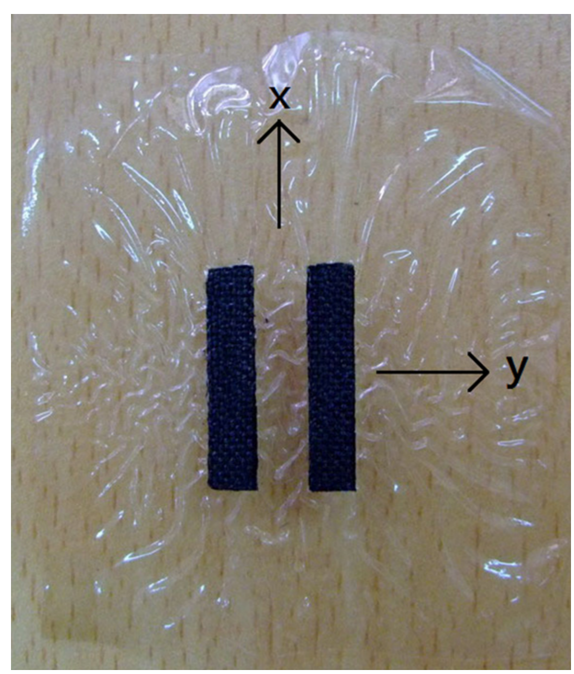

Fig. 11. Banded MEA with two bands.

or channel. This is particularly important for an air breathing portable fuel cell.

In addition to the above advantages, the carbon fibre current collector is also lightweight and inexpensive to produce.

2.2. Spring retainer

A spring retainer is used to position the flexible current collector and also to exert a constant pressure on it to maintain close contact with the electrode when the main body changes its shape. This pressure does not need to be large because, once the soft carbon fibre touches the carbon cloth of the electrode, a larger pressure will not significantly increase the number or change the distribution of the contacts. As a matter of fact the pressure can be exerted using the metal wire connecting the carbon fibre lumps. However, as the shape shifts from convex to concave, the spring retainer will be helpful in maintaining contact during cell operation. As shown in Fig. 7, the retainer is shaped in such a way that it can accommodate the relative movement between the MEA and the main body.

2.3. Cell structure

Fig. 8 presents a schematic drawing of the cross section of the new cell. The cell is built on a square shallow cup-like structure (main body) made of an elastomer (e.g., EPDM). The membrane is glued to its inside rim. The volume thus formed between the MEA and the bottom of this main body will be the anodic chamber. The electrons generated on the anode will move out of the chamber through the current collector and its embedded metal wires. The collector is held in place by a spring-retainer, with its two ends fixed on the main body frame. The retainer also exerts a pressure on the collector to maintain a close contact with the electrode when the main body changes its shape. For a banded MEA, the longitudinal direction of the flexible current collector coincides with that of the banded electrode. A symmetrical arrangement is set up on the upper side of the membrane, i.e., the cathode, but it is open to the air.

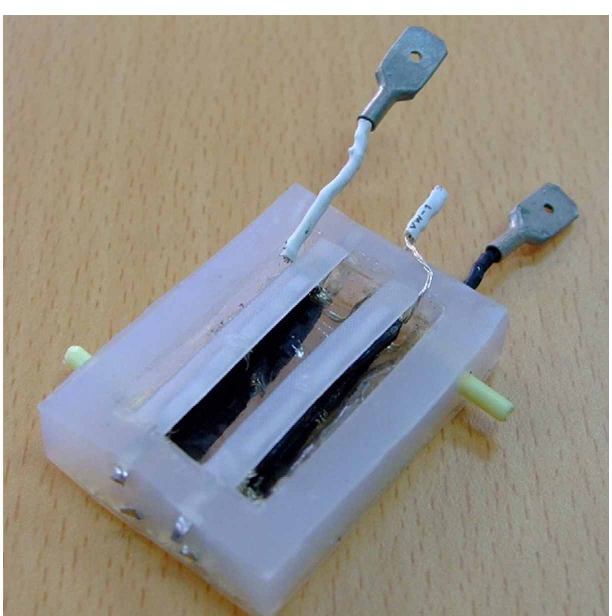

Fig. 12. Pilot flexible portable PEMFC.

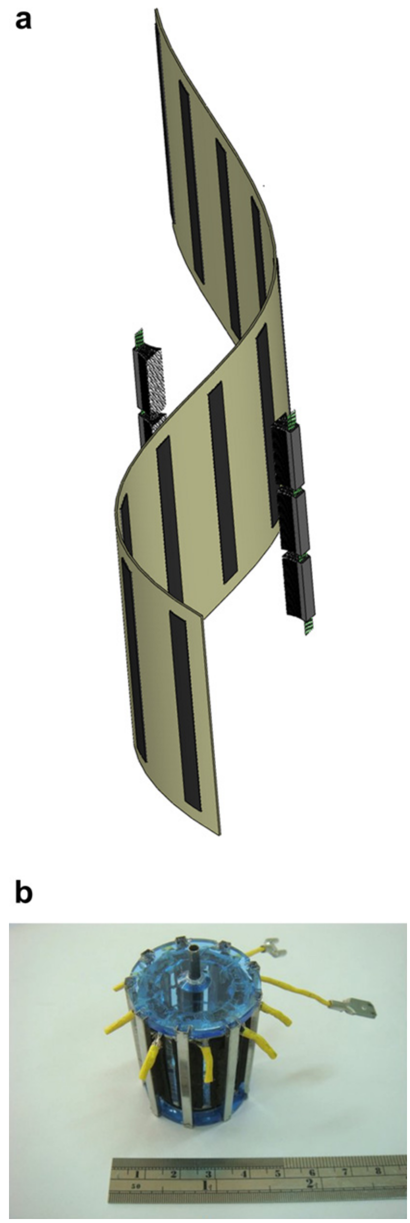

Fig. 13. (a) Banded MEA and the corresponding carbon fibre current collectors used in (b) a nonflexible cylindrical portable PEMFC.

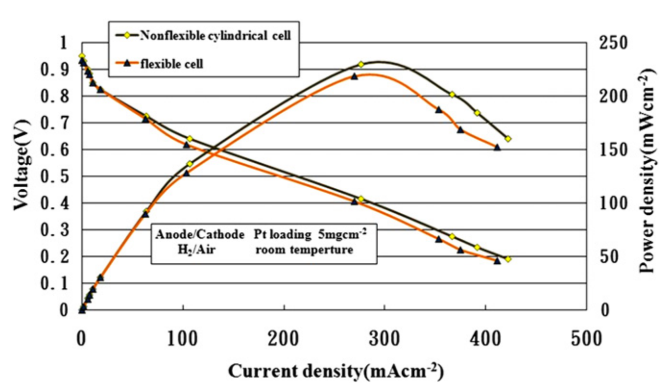

Fig. 14. Performance comparison between the nonflexible cylindrical cell and the flexible pilot cell.

3. Results and discussion

A pilot cell was fabricated and performance tested while bending at curvatures of different radii.

3.1. Pilot cell fabrication

A simple cell was constructed according to the structure introduced above, beginning with the manufacture of the flexible current collector.

3.1.1. Fabrication of the flexible current collector

Carbon fibres were first spread into thin layers and then stacked together layer by layer with epoxy and metal wire placed between layers, as illustrated in Fig. 9. After the desired thickness was reached, it was cured with heat under a very large compressional force. The cured epoxy bound the fibres and the metal wires tightly together to reduce the contact resistance between them. Experimental results shown that it is much smaller than the contact resistance between the electrode and the carbon fibre current collector. The amount of epoxy applied must be carefully controlled such that the other end of the fibre is free of epoxy and remains soft and flexible. The length of this soft epoxy-free portion will determine how well it can fit the curved electrode. In the pilot cell the current collector is divided into two lumps, as shown in Fig. 10.

3.1.2. MEA

To accumulate a higher output voltage, the pilot cell uses a banded MEA [14] with two bands of electrodes (each 0.4 cm wide by 2.5 cm long) sharing the same membrane, as shown in Fig. 11. Only one current collector is needed for each electrode band and their longitudinal directions coincide. The Pt loadings for both anode and cathode (E-Tek) are 5 mg cm^{-2} so that their performance may be compared with that of the cylindrical cell fabricated earlier.

3.1.3. A pilot flexible cell

As shown in Fig. 12, the pilot cell was constructed according to the structure illustrated in Fig. 8. The cell weighs 12 g and its dimensions are 4 × 3 × 1 cm (l/w/h). The total electrode area is 2 cm^2 and the maximum output power is 0.4 W.

3.2. Performance comparison with a nonflexible cylindrical portable cell

To investigate what this “flexibility” costs in terms of cell performance, the pilot cell is compared with a nonflexible cylindrical portable cell composed of similar components. The basic structure of a cylindrical portable PEMFC has been introduced earlier [15], and it may be considered a conventional flat cell curled into a cylindrical shape. With all the cathodes facing outward for easy access of air, the inner space is the anode chamber with both

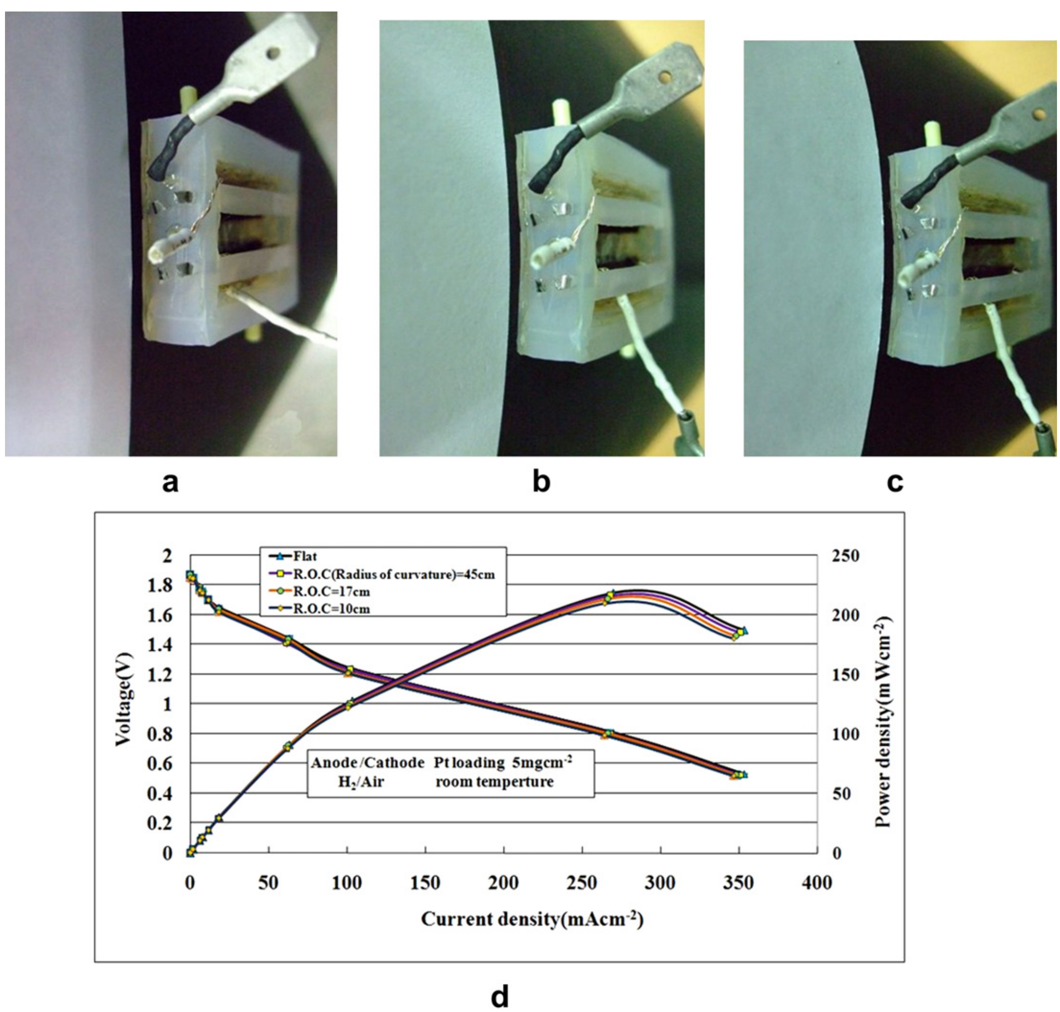

Fig. 15. Cell bends about the *x*-axis with radius of curvature of (a) 45 cm, (b) 17 cm, (c) 10 cm, and (d) their corresponding performances.

ends capped. Using a banded-type electrode may obtain a higher voltage output. The longitudinal direction of the carbon fibre current collector coincides with that of the banded electrode and the axis of the cylindrical cell. Fig. 13 shows a cylindrical cell using the same design and fundamental elements as in the cell using the flexible carbon fibre current collector. As shown in Fig. 14, the flexible structure does not significantly hamper cell operation.

3.3. Effect on performance when cell bends about two orthogonal directions

The pilot cell was tested when bending about two orthogonal axes with curvatures of different radii to examine the effectiveness of this flexible cell design. One axis runs along the longitudinal direction of the current collector, shown as the *x*-axis in Fig. 11, which is also parallel to the longitudinal direction of the banded electrode. The other runs along the transversal direction of the current collector, shown as the *y*-axis in Fig. 11.

3.3.1. Bending about the longitudinal direction of the current collector

When the cell bends about an axis parallel to the longitudinal direction of the collector (i.e., the *x*-axis shown in Fig. 11), several collectors with longitudinal directions parallel to the bending axis may be used to cover the entire curved electrode area. For the electrode area directly under each collector, coverage depends on the surface, formed by the tips of the collector's millions of soft carbon fibres, to deform to match the curved surface. That is, the fibres at the central portion of the fibre bunch will be compressed on the convex side while those at the two edges will do the same on the concave side. As long as the radius of curvature is not too small or the width of the collector is not too large, the performance of the cell is not expected to be seriously affected. Fig. 15 shows the performance of the cell bending at curvatures of different radii, resulting in only slight changes to performance.

3.3.2. Bending about the transversal direction of the current collector

When the cell bends about the transversal direction of the collector (i.e., the *y*-axis shown in Fig. 11), the shape of the current collector will be either convex or concave. In addition to the deformability of the soft fibres, the metal wires connecting the fibre lumps provide the flexibility required to match the curved electrode surface. Therefore, the length of each fibre lump and the number of lumps per collector will determine the contact conditions between the collector and the curved electrode. As shown in Fig. 16, since the current collector in the pilot cell is composed of only two lumps, performance drops slightly as the cell bends to

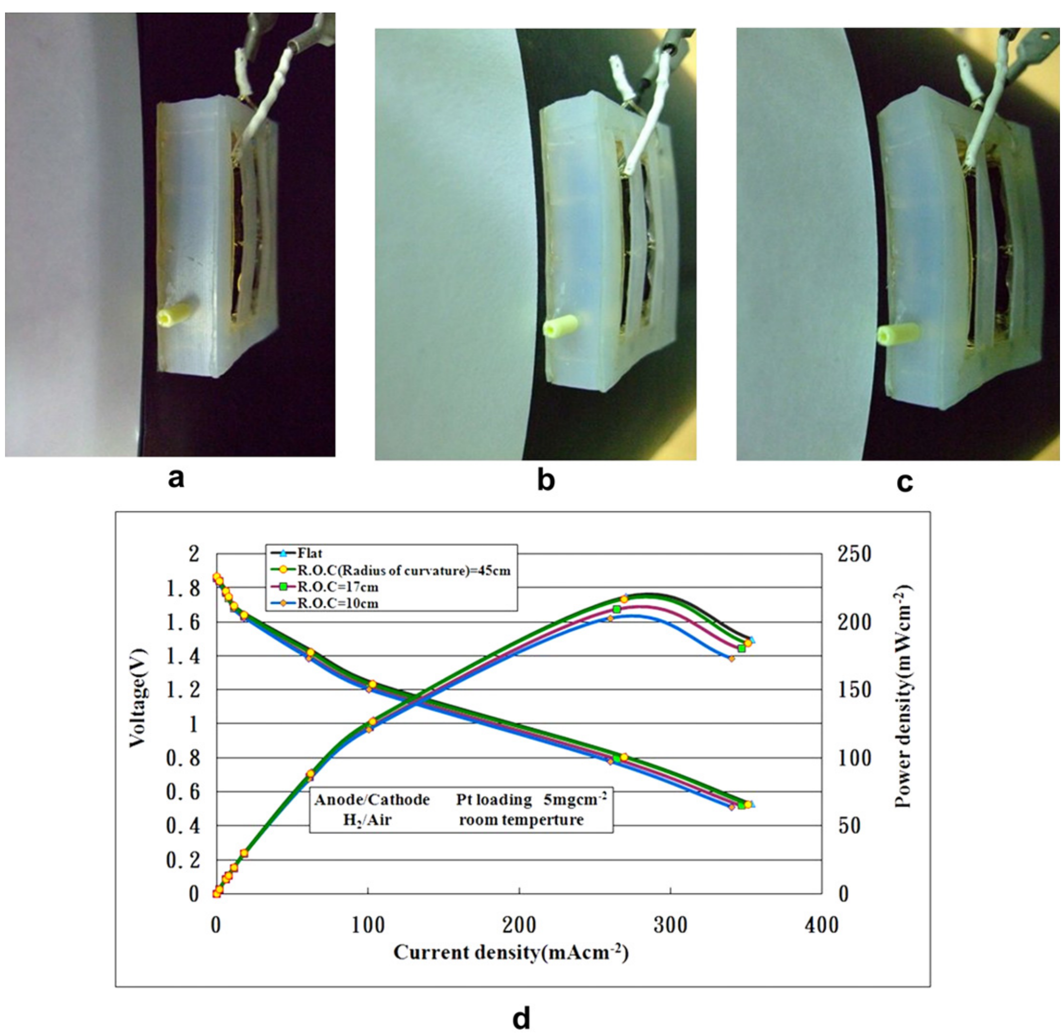

Fig. 16. Cell bends about the *y*-axis with radius of curvature of (a) 45 cm, (b) 17 cm, (c) 10 cm, and (d) their corresponding performances.

curvatures of a smaller radius, but this can be remedied by using smaller fibre lumps or more lumps per collector.

4. Conclusion

A portable PEMFC with limited flexibility in all directions is developed. The flexibility is acquired through the design of a new current collector and a new cell structure. The current collector is made of millions of soft and flexible carbon fibres and has a very low contact resistance under a small compressional force. A pilot cell suffers no significant performance loss when bending to curvatures of various radii in multiple directions. It also compares well with a nonflexible cylindrical portable PEMFC composed of similar major components.

Unlike the conventional stack design, the new cell is built on a single cup-like flexible main body and the edge of the membrane is glued to its inside rim to form an anodic chamber. The current collector is composed of several metal wire embedded carbon fibre bunches. A wire spring is used to position and pressure the collector against the electrode while the main body bends.

The key to the success of this flexible cell design is the development of the carbon fibre current collector because:

1. It changes the characteristics of the contact between itself and the electrode so that a large compressional force is no longer required for low contact resistance thus eliminating the need for heavy and bulky components. As a result, the stack can be light, small, variform and flexible.
2. The contact resistance of the proposed cell is lower than that of graphite, carbon composite or metal plates, or any plates with flat and relatively hard surfaces because the contact resistance is largely determined by the evenness of the distribution of the contact points. The soft carbon fibre tips ensure close and evenly distributed contact with the electrode's rough surface. Higher pressure will not reduce resistance further once all the fibres have made contact.
3. The soft and flexible fibres can adapt to the curvature of the electrode's surface. The metal wire connecting the fibre lumps provides the flexibility needed for a large curved area.

The new cell is very thin, light and inexpensive. It contains no brittle elements, making it very suitable to be attached to the curved surface of a belt, bag or backpack. It can also be used as a DMFC.

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